CRYOGENIC MAGNETOSTRICTIVE ACTUATORS: MATERIALS AND APPLICATIONS

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Abstract:
Magnetostrictive actuators based on TbDy alloys show promise for use as actuators in cryogenic devices. They can be made to deliver large forces and useful displacements below liquid nitrogen temperatures, with many advantages over piezoelectric actuators or motion feedthroughs from higher temperature actuators. We present our most recent developments in materials processing and characterization, including the development of polycrystalline materials which show substantial magnetostriction and can be produced at much lower cost than single-crystal materials. We also show several magnetostrictively-actuated devices intended for use at low temperature: a liquid helium valve which has been demonstrated to be leak tight at 4.2 K; a linear stick-slip motor; and a linear positioner which uses the stick-slip drive approach to rotate a "threadless" lead screw.

Introduction

In recent years there has been considerable interest in applying the large strains associated with magnetostrictive rare earths to low-temperature actuator applications such as liquid helium valves, which operate at or below 4.2 K, and micropositioning devices for IR satellite optics, which operate at 50 K and below. Traditional actuator materials such as piezoelectrics perform marginally at or below liquid nitrogen temperatures and are best at room temperature. The advantages of having a cold prime mover which is maximimally effective at temperatures which are identically those of the cryogenic working fluid, sample, focal plane or experiment to be moved are are the driving force behind research in low-temperature rare earth magnetostrictive actuators. The joint application of magnetostrictive materials and high-T_C superconductors (HTSC) comprise a highly effective approach to low temperature actuation. TbDy alloys exhibit saturation magnetostrictive stroke approaching 1.0% of actuator length at low temperatures [1], but the preparation of single crystals is difficult and expensive.

The Next Generation Space Telescope (NGST) may require as many as 2000-3000 cryogenic actuators for the flight telescope. Since it is not possible to produce single crystals in such numbers either for NGST or for other applications of interest, our objective is to develop textured polycrystals for use in actuator applications. Polycrystalline $Tb_{0.6}Dy_{0.4}$, cold rolled to induce crystallographic texture, has shown magnetostrictions of 0.2% of actuator length at a temperature of 10 K. Even with this fraction of the single crystal performance, the polycrystalline samples have two major advantages. First, large samples of greatly varied shape can be prepared easily and at low cost. Second, polycrystalline TbDy alloys may not require an applied spring force in order to return to an unstrained state. The use of the internal strain energy stored at the grain boundaries as a return spring simplifies the engineering design of these actuators.

Materials Preparation and Costs

Growth of hexagonal single crystals of TbDy alloys is difficult due to a high temperature cubic phase region. Since Tb has an easy <10-10> direction of magnetization while Dy has an easy <2-1-10>, an alloy ratio can be chosen to minimize the anisotropy in the basal plane for each temperature range of operation; for instance the estimated minima occur at $Tb_{0.76}Dy_{0.24}$ for 4 K, $Tb_{0.6}Dy_{0.4}$ for 77 K [2]. The Tb and Dy are arc melted in the desired ratio, and then dropped into a chilled copper mold. The resulting ingot (1" diameter and several inches long) is then deformed and sealed into a Ta crucible. The material is heated to 1300°C for several days in order to induce grain growth. If a large grain grows, a crystal with the c-axis perpendicular to the rod axis may be cut from the ingot. The growth process is not easily controlled and results vary widely depending on the size of the grains and their orientation within the ingot. It is, therefore, not feasible to implement on a large production scale. Single crystals ¼" diameter and 1" long may cost upwards of $5000. Because impurities inhibit grain growth, high purity material is required for the single crystal growth process [3]. Commercial grade material has a total purity 99.7%, with the main impurities being Ta, O, and N, whereas the high purity material has a total purity of 99.94%. High purity Tb (Dy) costs $24/gm ($9/gm) from Ames Laboratory Materials Preparation Center as compared to $4/gm ($1/gm) for commercial grade. This represents a considerable expense, as only a small portion of the starting material eventually becomes a single crystal suitable for use in devices, with the remainder contaminated in the process and therefore unsuitable for future attempts.

For production of polycrystals, the TbDy alloy is also arc melted and dropped into a chilled mold. Since the as-cast ingot shows strong texture, the material is first deformed by 35% and heat treated for 1.5 hr at 950°C to induce recrystallization. This is thought to result in a somewhat more random initial orientation of spherical grains, although our bulk thermal expansion measurements indicate that significant texture remains. The specimen is then form-rolled or plane-rolled by 0-55% and heated to 350°C in order to relieve strain. One advantage of this technique is that commercial rolling and drawing processes are reliable and repeatable. The texture of the material is critical due to the elastic interactions of misaligned grains and the large anisotropy of the material. At liquid helium temperatures a 10 Tesla field produces less than a 10% deflection from the basal plane [4]. In contrast to the single crystals, the cost of preparation of the polycrystalline materials is as low as a few hundred dollars, with potential for further reductions when production techniques are optimized. The production of polycrystalline magnetostrictive materials by deformation processes and some applications of these materials are the subject of a provisional patent by the authors and JPL.

Experimental Methods

The materials were characterized with a low temperature test facility, which consists of a cryogenic dilatometer outfitted with accessory measurement devices. The measurement apparatus consists of a helium dewar and optical probe assembly designed in cooperation with Janis Research, Inc., Wilmington, MA, with a Polytec laser vibrometer configured for measuring linear displacement and a flexure stage for mounting the reflector for the laser. A load is applied via a mechanical system and measured with a strain gauge load cell. The dewar and probe assembly is constructed so that an experiment volume of 30 cm diameter and 30 cm deep is available atop a large liquid helium reservoir. There is an optical path from the top of the apparatus to the top of the helium reservoir. In order to work with the current low T_C superconducting coil, the solenoid housing has been modified to allow a continuous flow of helium to surround the solenoid. This configuration is suitable for measurements on magnetostrictive materials and other actuators at lower temperatures, with the specimen temperature between 4 and 20 K, estimated for the data presented here to be 10 K.

The data aquisition and instrument control software was written as a configuration of virtual instruments in Labview™. The programs run and log the current input to the coil, magnetic field, and crystal displacement data at 50 Hz. The input current to the field coil can be voltage controlled by the program or the operator on the front panel. The control has been implemented on a Pentium™ based computer equipped with Lab-PC+ and GPIB interface card.

Material Performance

A single crystal of $Tb_{0.6}Dy_{0.4}$ was found to exhibit a saturation magnetostriction of 8800 ppm at a field of 3 kOe with an applied stress of 27.5 MPa, as shown in Fig. 1. The textured polycrystalline specimen requires higher fields to saturate the material than can presently be produced in our test apparatus. At the highest field available, 3.8 kOe, and with an applied stress of 22.6 MPa the polycrystalline specimen shows a magnetostriction of 1850 ppm. Even at 2 kOe applied field, textured polycrystalline $Tb_{0.6}Dy_{0.4}$ specimens produce magnetostrictions

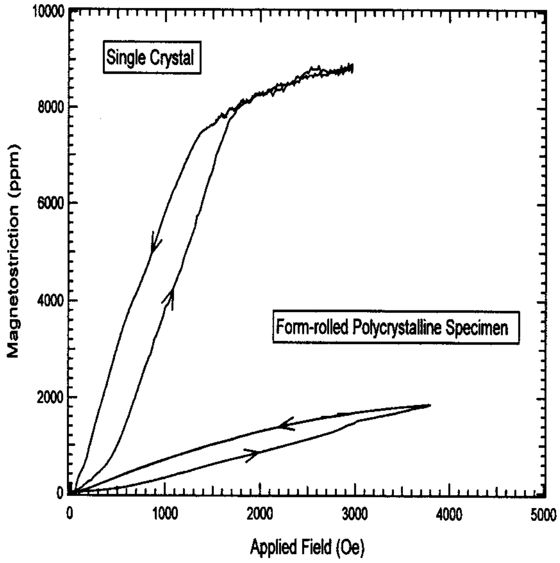

***Fig. 1:** Magnetostriction of $Tb_{0.6}Dy_{0.4}$ single and polycrystalline specimens.*

useful for many engineering applications. The magnetostrictive stroke observed is dependent on the texture of the polycrystal, and plane-rolled specimens are expected to give higher magnetostrictions than the form-rolled specimen shown here for the same field and applied load. For an applied field of 2 kOe the textured polycrystalline material shows a magnetostriction of 1000 ppm at cryogenic temperatures which compares well to that of Terfenol which has a magnetostriction on the order of 2000 ppm at room temperature.

As shown (see Fig. 2), with applied fields of 2 kOe, magnetostrictions of 850 ppm are possible with an applied load of 1.9 MPa, as compared to 1000 ppm with an applied load of 22.6 MPa at 10 K. Polycrystalline $Tb_{0.6}Dy_{0.4}$ does not require a large applied stress in order to return to an unstrained state, unlike single crystals. It is necessary to include preload stresses in the design of devices in order to make engineering use of the large magnetostrictions of the single crystals. The microstructural origin of this "internal spring" is under investigation, but we expect a relation to elastic interactions between neighboring crystallites. It is possible that the need for a preload can be eliminated entirely by controlling the texture of the specimen.

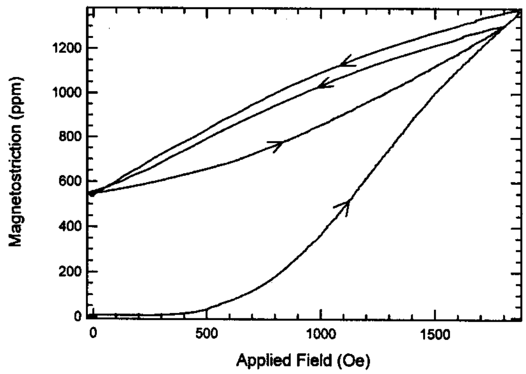

***Fig. 2:** Magnetostriction of polycrystalline specimen for an applied load of 1.9 MPa at 10 K.*

Demonstration Devices

Several demonstration devices have been developed and tested. They include a helium valve, a linear stick-slip motor, and a heat switch for use at cryogenic temperatures, from 4-77 K. We first tested most of the devices at room temperature with a Terfenol-D crystal replacing the low temperature TbDy alloy. Then the device is tested with a single crystal actuator at low temperatures. Low temperature tests with a polycrystalline specimen replacing the single crystal actuator in the liquid helium valve will begin shortly.

The helium valve is designed for applications which require minimal thermal disruption by valve actuations. Both the valve body and the actuator mechanism of the valve are modular, so that design changes may be made to either section of the valve with no modification of the other element. The side of the valve to which experiments may be attached has a dead volume of approximately 20 microliter. When used with a superconducting solenoid, the heat dissipated is limited to the heat produced at the valve seal itself, and for liquid helium applications, the heat leak due to the presence of the valve is eliminated by the use of superconducting current leads.

The valve body is composed of a seat made from super-refined 316L stainless steel with a .030" reamed bore. The seat surface is then polished to an optical finish and mated with the upper part of the valve body. The upper part of the valve body contains a 440C steel ball of 0.13 micron sphericity and 0.013 micron roughness, which is used to make the seal against the valve seat. The seat is "coined" by loading the ball with a greater force than will later be used to seal the seat. A post which transmits force to the ball protrudes from the upper part of the valve body, where it is mated to the actuator mechanism. Belleville springs between the actuator and the post hold the valve normally-closed. The ball is prevented from rotating by its attachment to the post, and thus corresponding parts of the ball and seat maintain the same orientation with each other, such that the match between seat and ball geometry is preserved.

The outer part of the actuator mechanism is composed of a stainless tube welded onto the pedestal, which mates with the body of the valve. A second, sliding tube is nested inside of the outer tube, and the magnetostrictive crystal is located within the inner tube. A set of concentric tubes and cross-pins transmits force from the crystal to lift the ball from the seat. A solenoid mounted around the outer tube is used to apply the magnetic field for actuation. When the solenoid is energized, the crystal expands along its length, pushing the inner tube upwards opening the valve.

We have used an HTSC coil, producing approximately 0.125 kOe/A to operate the valve at 77 K for more than 300 open/close cycles with no degradation of the seal. The helium leak rate when closed is less than 10^{-9} std-cc/s (limited by the resolution of the leak detector). The valve opens with approximately 2 kOe applied field. After the 300 open/close cycles at 77 K, the HTSC coil was replaced with a NbTi low-temperature superconducting coil (~1 kOe/A) and tested 4 open/close cycles in liquid helium, with the experiment side of the valve open to the liquid. Testing in liquid helium is limited by the leak tester pumping time after each open/close cycle. The valve remained leak tight to 10^{-9} std-cc/s.

A room temperature working demonstration model of a linear stick-slip motor has been developed. As a class these devices are sometimes known as inertial reaction motors. The device operates by moving a reaction mass rapidly with respect to a carriage, so that the carriage, which sits on tool steel balls, slips along on highly polished sapphire rails. The reaction mass is then slowly returned to its initial position. The static friction between the bearings and rails keeps the device in place during the return cycle of the reaction mass. By varying the acceleration the reaction mass, the rate of displacement of the carriage can be controlled. The driving waveform is a simple sawtooth function. The waveform is reversed to change the direction of motion. With a 1.5 kg chassis mass, translations as small as 50 nm have been demonstrated.

The fundamental design concept for the linear positioner is the rotation of a "threadless" lead screw using a stick-slip drive approach. The mechanism is composed of a rotating shaft held in place by six roller bearings mounted skew to the shaft axis. The skew axes of the bearings sit along a helix which is concentric to the central, rotating shaft. When this shaft is rotated along its axis the skewness of the bearings cause the shaft to advance. A low friction Rulon sleeve bearing is attached to the arm of a magnetostrictive actuator and used as a friction pawl against a flywheel mounted on the shaft.

When driven with a saw tooth voltage signal, the actuator produces a continuous stepped rotation of the flywheel. Incremental rotations in the lead screw shaft results in small consecutive linear steps. The linear positioner is operational at 300 K with a resolution of 10 nm. This device is expected to function as well or better at temperatures to 4 K because of the enhanced properties of the actuator material at helium temperatures.

Displacement measurements, shown in Fig. 3, were performed using a laser vibrometer with 8 nm resolution. Each step contains 25 cycles from the actuator for a net displacement per step of 770 nm and a mean displacement of 30 nm per cycle. A filter-wheel driver operating on a similar principle has been demonstrated from 77-300 K with arcsecond resolution.

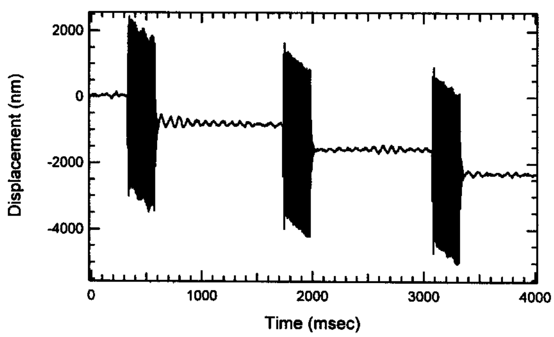

Fig. 3: Stepped motion of linear positioner over a four second interval.

Conclusion and Results

There is currently a demand for a large number of low-temperature magnetostrictive devices, in applications as helium valves, and micro-positioners for space telescopes. Textured polycrystals show promise for replacing single crystals in these actuators at a significantly reduced cost. Additionally, the advantage of eliminating the need for preload mechanisms in certain applications would reduce the cost and weight of the devices. Single crystal $Tb_{0.6}Dy_{0.4}$ has been shown to exhibit a saturation magnetostriction of 8800 ppm at 10 K.

I think it's no "s."

Acknowledgments

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